Chapter 12
Alternative Powertrains

At present, the large majority of road vehicles are powered by fossil fuels derived from oil, even if a growing number of electric vehicles and of vehicles powered by alternative fuels can be seen on the road. Since these alternative energy sources and vehicle schemes are more a perspective for the future than a reality of today, a thorough discussion on these topics will be reported in Part III. In the following sections, however, the existing propulsion systems that are alternative or complementary to engines burning fossil fuels will be outlined, including electric and hybrid vehicles and vehicles propelled by fuel cells and gaseous fuels.

12.1 Battery Electric Vehicles

Electric vehicles are once again arousing the interest of car manufacturers worldwide for the role they may have in satisfying the demand for mobility and the need for virtually zero impact on air quality in urban areas. The advantages of electric vehicles are linked primarily to the possibility of moving the pollution from where the vehicle is used to where the power is generated, taking advantage of the better pollution control of power stations versus small engines. Another advantage is the possibility of regenerative braking.

The disadvantages are also well known: The performance of electric drives is affected by losses in both the engine and the batteries, and above all by the difficulties batteries have in delivering high power and, even more, accepting the power bursts that occur in braking. The quantity of energy that can be actually recovered by regenerative braking is thus only a fraction of that theoretically available. The main limitation of electric vehicles is still a number of characteristics that caused their use to be practically discontinued at the beginning of the twentieth century; their reduced range, the limited duration and high cost of the batteries and their high mass. However the performance of electric vehicles is sufficient for urban use.

G. Genta et al., *The Motor Car*, Mechanical Engineering Series,
DOI: 10.1007/978-94-007-8552-6_12,

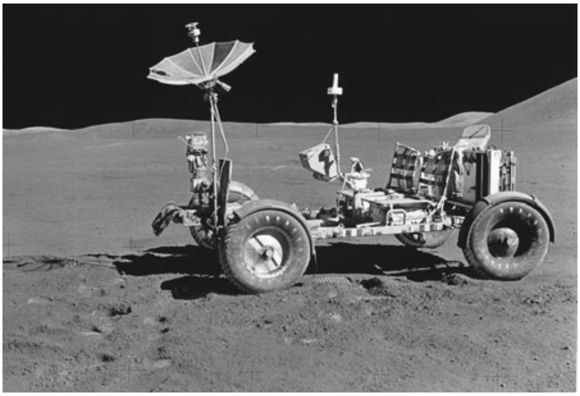

Fig. 12.1 The LRV, designed and built by Boeing at the end of the 1960's, was used on several *Apollo* lunar missions during the 1970's (courtesy of NASA)

From the point of view of energy the advantages of battery powered electric vehicles (BEV) are still in doubt: When the primary source is a fossil fuel, in spite of the greater efficiency of the primary conversion and regenerative braking, the overall consumption is comparable to, and usually higher than, that of internal combustion engines. This point will be dealt with in detail in Sect. 14.1.

A technical review of modern vehicular electric drive systems can start with the description of an absolutely special, emblematic electric vehicle: the Lunar Roving Vehicle (LRV) used on the Moon by the Astronauts of the last *Apollo* missions (Fig. 12.1). It was first used during the *Apollo 15* mission, which lifted off on July 26, 1971 launched by a *Saturn V* rocket. The mission landed on the Moon 4 days later, on July 30, near the Hadley Range and returned to Earth on August 7, after approximately 12 days in space and 3 days on the Moon. They orbited twice around Earth and 74 times around the Moon. Mission Commander David Scott and astronaut James Irwin travelled a total distance of approximately 30 km on the surface of the Moon using the LRV (astronaut Alfred Worden remained in orbit around the Moon on the command module) collecting approximately 80 kg of lunar soil samples along the way.

The LRV was designed and built by Boeing at the end of the 1960's. Its main specifications were:

- Empty mass: 240 kg (weight: 2350 N on Earth, 360 N on the Moon); payload mass (two astronauts and equipment): 490 kg;
- Length: 3.1 m; width 1.8 m; height 1.1 m; wheelbase 2.3 m;
- Multilayer metallic mesh wheels, reinforced with titanium alloy chevrons for traction;
- Four independently suspended and steering wheels, steer-by-wire system;
- Four electric motors, one for each wheel, 18 kW each;
- Traction batteries: two 36 V silver-zinc type;
- Range: 65 km;
- Maximum speed: 17 km/h;

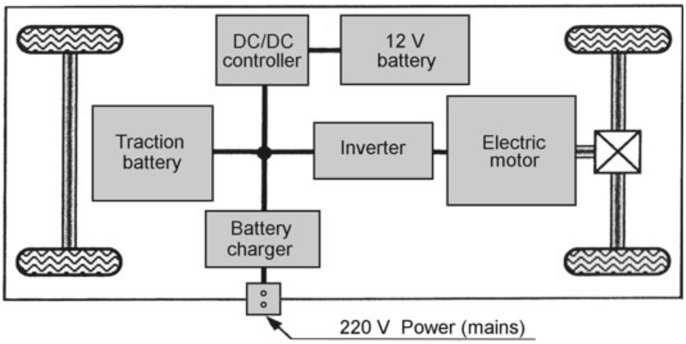

Fig. 12.2 Scheme of the propulsion system of an electric car

Owing to the short planned duration and range, the vehicle had primary (non rechargeable) batteries: the high energy density of this kind of batteries made it possible to keep the mass of the vehicle to a minimum. The LRV was a strange mix of very advanced features, anticipating some trends that may in the future become common in the automotive field, and simple solutions that at that time already belonged to the past. For instance, it had four-wheels driving and steering, but the steering control was based on kinematic steering; it had a steer-by-wire control, but the brakes were operated by cables.

Apart from this, very peculiar, vehicle, electric cars always had their small niche in the automotive market, having lost the large share of the market they had at the beginning of the twentieth century (see Part I). The biggest problem electric vehicles always had to face is the low performance of lead-acid electric batteries, the only rechargeable batteries that, until not many years ago, could be realistically used in the automotive field. This situation is now changing, owing to new battery types that are now available (see Chap. 13).

The most important problem to be solved in designing the layout of Battery Electric Vehicles (BEV) is battery installation, because of their significant volume and weight. The best results can be obtained only if the vehicle is specifically designed as a BEV from the beginning or, at least, if, in the design of the electric versions of a conventional car, provisions are taken to find space for the batteries at the very beginning of the development process.

The scheme of a very simple electric drive system is shown in Fig. 12.2; it essentially consists of a number of traction batteries, an inverter, a three-phase asynchronous electric motor and a DC/DC electric converter. The inverter is an electronic device converting direct voltage from the traction battery into three-phase, alternating, regulated voltage for powering the asynchronous motor; the DC/DC converter converts traction battery voltage into a lower voltage (12 V) for recharging the service battery.

Three-phase asynchronous motors are preferred to the direct current motors used in vehicular applications in the past because they:

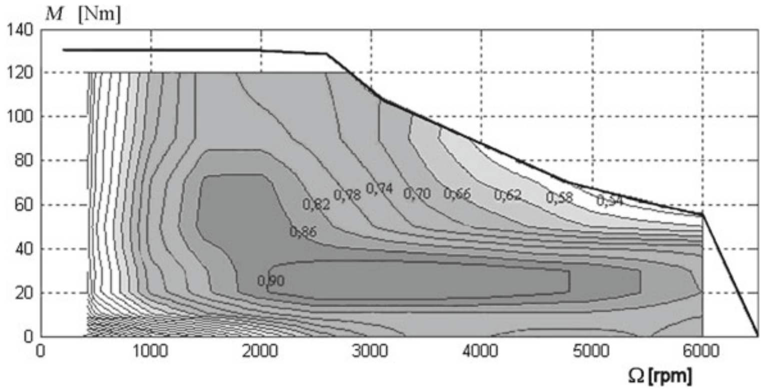

Fig. 12.3 Operating map of an induction AC electric motor. Plot of the torque M as a function of the speed Ω, with constant efficiency lines (from Genta and Morello 2009)

- are more compact, lightweight and have a high specific power;
- have a wide operating range at constant power;
- have a better energy efficiency and
- are highly reliable and, due to the absence of brushes, are virtually maintenance-free.

These advantages are even more marked if a brushless DC motor is used, like in the more advanced applications.

Since the electric motor can start under a load, there is no need for a clutch and usually no need for a gearbox with more than one transmission ratio. The asynchronous motor can thus be conveniently arranged on the rear end of the vehicle, if the rear wheels are the driving ones. It drives the rear wheels via a mechanical one-speed gearbox and a differential unit.

The map of the efficiency of an induction traction AC motor with a nominal power of 35 kW is shown in Fig. 12.3. The efficiency is much less sensitive to operating conditions (speed Ω and torque M) than in conventional internal combustion engines. However, also in this case a variable speed gearbox could help in achieving the best fuel efficiency.

As an alternative to this traditional architecture, with the motor operating the wheels through a mechanical transmission, it is possible to put two or more motors directly in the wheels. As an alternative, instead of locating directly the motors in the wheels, where they increase the unsprung masses, there can be one electric motor per wheel located under the vehicle body, driving the relevant wheel through a half-shaft. This configuration was suggested and tried several times in the past with limited success except for special vehicles, but it seems to be ready for large-scale application today.

At any rate, traditional or brushless DC or AC motors require a mechanical transmission, since they supply an insufficient torque and operate at a speed that is higher than that of the wheels. High torque motors (torque motors, both with

internal and external rotor) that can be connected directly to the wheels without an interposed reduction gear are at present available. Apart from the advantage, which may be important in some applications, of allowing an arbitrarily large steering angle, even up to 360°, putting the motor in the wheels without using a reduction gear leads to high efficiency, low noise and a large degree of freedom in placing the various subsystems on the vehicle. Torque motors are, however, still heavier than high speed motors plus the required reduction gear and imply an increase of the unsprung masses, which is detrimental to both handling and comfort: direct drive, torque motors seem to be more a perspective for a future, nobody knows how far, than a possibility for today. When two electric motors operate the two wheels of the same axle, either located on the wheels or attached to the body and operating the wheels through semi-shafts, the motor control system can perform the electronic differential function, distributing the torque to the wheels of the axle, possibly simulating all the functions of a limited slip (or in general controlled) differential.

Apart from the traction batteries, that supply a voltage in the range $96 \div 300$ V, on board electric vehicles there is usually a 12 V battery powering all services. A DC-DC converter transforms high voltage direct current into 12 V direct current, for keeping the low-voltage battery charged. This redundancy is due to the need to ensure emergency operation with flat traction batteries and also for safety reasons: high voltage must be confined to the few points where it is absolutely needed, and even so the dangers of high DC voltage in electric cars must not be understated. The choice of 12 V for low voltage accessories is also motivated by the economic advantage of using components that are standard in existing vehicles.

Traction batteries may be recharged either by the on-board battery charger, from the AC mains at 220 V, or by a dedicated fixed system which powers the DC batteries directly. Eighty percent of the maximum battery charge is reached in approximately 4 h while the time needed for a complete recharge cycle is about 8 h. Batteries must be fully recharged frequently during normal vehicle use to ensure good battery performance; the batteries may be conveniently recharged at night. Modern (non lead-acid) batteries require careful charging and sophisticated chargers are used both for improving the whole charge-discharge process and for safety.

Each major car manufacturer has electric cars on the market or, at least, under development: Renault, taken as an example, presents a very complete range, now on sale on selected European markets. The models of this range, whose pictures are shown in Fig. 12.4, are many and feature technical specifications not so different from their internal combustion engine counterpart, as shown in Table 12.1.

When electric vehicles are compared with conventional vehicles on the grounds of performance, flexibility, comfort and safety levels their traditional shortcomings, namely: heavy weight, low range, long battery recharging time and high costs, are still there and it is predictable that this situation will improve slowly, as it will be shown in Part III.

Fig. 12.4 The range of electric vehicles produced by Renault are not so different from they conventional counterparts (courtesy of Renault)

Table 12.1 Specifications of the Renault electric vehicles available for sale in selected European countries

Name	Fluence	Zoe	Twizy	Kangoo
Type	Large sedan	Compact sedan	Quadricycle	Van
Length [mm]	4,748	4,086	2,337	4,213
Width [mm]	1,813	1,788	1,237	1,828
Power [kW]	70	60	13	44
Torque [Nm]	226	222	57	226
Top speed [km/h]	135	135	80	130
Range [km]	185	160	96	170
Seat number	5	5	2	2
GVW [kg]	1,543	1,392	450	1,410
Cargo	–	–	–	650 kg

12.2 Traction Batteries

Electrochemical batteries are devices in which an electric current is generated as a consequence of a chemical reaction occurring between two reactants. An example of the electrochemical reaction is that taking place in lead acid batteries in which, when fully charged, the anode is made of lead, the cathode is made of lead oxide and the electrolyte is diluted sulfuric acid (in the form $H_2SO_4 \rightarrow H^+ + HSO_4^-$). During discharge, both plates are turned into lead sulfate, releasing electrons at the anode and getting electrons at the cathode. The reactions are:

$$\begin{array}{ll} Pb + HSO_4 \rightarrow PbSO_4 + H^+ + 2e^- & \text{Anode,} \\ PbO_2 + HSO_4 + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O & \text{Cathode,} \end{array}$$

i.e., as an overall reaction,

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O\ .$$

Like in all secondary (rechargeable) batteries, this chemical reaction is reversible and can be run backwards by passing a current through the cell. This decomposes the lead sulfate into lead and lead oxide, through the reactions

$$\begin{array}{ll} PbSO_4 + H^+ + 2e^- \rightarrow Pb + HSO_4 & \text{Anode,} \\ PbSO_4 + 2H_2O \rightarrow PbO_2 + HSO_4 + 3H^+ + 2e^- & \text{Cathode.} \end{array}$$

This reversibility is never complete, like in all rechargeable batteries, and the battery cannot be recharged an infinite number of times: at every recharge the performance of the energy conversion somewhat deteriorates until the cell cannot be recharged any more. The performance of any battery depends on many factors and, above all, its capacity is affected by how fast the charge and discharge process is performed.

At present, the types of secondary batteries that are available or are predictable for the near future are:

- Lead-acid cells. They were used for almost all ‘old’ electric vehicles and also the attempts to revive them were based mostly on batteries of this kind. While in origin they were based on an open container full of electrolyte (sulfuric acid), more modern types are sealed and provided with a valve to prevent pressure build up. The electrolyte can be semi-solid (gel) or can be absorbed in a special fiberglass matting. Their success is mainly due to their relatively low cost, low maintenance, safety and easy handling, their manufacturing simplicity and their interesting electrochemical features.
- Nickel-based cells. A wide family of rechargeable batteries are based on nickel chemistry, like nickel-cadmium (NiCd),[1] nickel-iron (NiFe), nickel-zinc (NiZn), nickel metal hydride (NiMH) cells. NiCd batteries are no longer legal, because of the ban on cadmium, while nickel-metal hydride batteries are becoming increasingly popular: For the same weight, these batteries double the vehicle range, with respect to lead-acid batteries at the disadvantage of a higher cost.
- Rechargeable alkaline cells. They are seldom considered for applications in which a large quantity of energy has to be stored.
- Lithium-based cells. They include lithium-ion (Li-ion), lithium ion-polymer (LiPo), lithium-iron-phosphate (LiPh) and lithium-sulfur (LiS) cells. In general the electrodes are made of lithium cobalt (or manganese, or nickel or iron) oxide and of carbon, in different forms. The electrolyte is made by lithium salts in a

[1] Actually NiCd is a proprietory name and should not be used to indicate NiCd cells in general.

Table 12.2 Main characteristics of some types of secondary batteries (e/m: mass energy density, e/v: volume energy density, P/m: power density, V: cell voltage, η: charge/discharge efficiency, d: self-discharge, c: number of cycles)

Type	e/m (Wh/kg)	e/v (Wh/dm^3)	P/m (W/kg)	V (V)	η (%)	d (%/month)	c
Lead-acid	30–40	60–70	180	2.0	70–92	3–4	500–800
NiCd	40–60	50–150	150	1.2	70–90	20	1,500
NiFe	50	–	100	1.2	65	20–40	–
NiZn	60	170	900	1.2	–	–	100–500
NiMh	30–80	140–300	250–1,000	1.2	66	30	500–1,000
Alkaline	85	250	50	1.5	99	<0.3	100–1,000
Li-ion	150–250	250–360	1,800	3.6	80–90	5–10	1,200
LiPo	130–200	300	3,000	3.7	–	2.8–5	500–1,000
LiPh	80–12	170	1,400	3.25	–	0.7–3	2,000
LiS	400	350	–	–	–	–	100

liquid organic solvent or in a solid polymer. The basic reactions, referred to 1 mol (which explains the coefficient x), are:

$$\begin{array}{ll} LiCoO_2 \rightarrow Li_{1-x}CoO_2 + xLi^+ + xe^- & \text{Anode,} \\ 6C + xLi + xe^- \rightarrow Li_xC_6 & \text{Cathode.} \end{array}$$

The use of Li-ion batteries is expected to provide a threefold increase in vehicle range for the same weight

As a general consideration, nickel based batteries have a larger self-discharge, while lithium batteries are better from the viewpoint of quick charging and discharging. The highest energy density, i.e., the ratio between stored energy and mass, is obtained from lithium-sulphur cells that, however, have a short life in terms of cycles.

The main characteristics of some types of secondary batteries are reported in Table 12.2; a plot of the mass energy density versus the volume energy density is reported in Fig. 12.5.

The energy density, and even more the power density of batteries is much lower than those of gasoline or diesel fuel: for the energy density the figures are $30 \div 200$ Wh/kg against approximately 13,000 Wh/kg. In addition, liquid fuel tanks can be filled in a matter of minutes, in comparison with the 4 or 8 h needed for electric batteries. If a range of $\sim$120 km is deemed necessary to accomplish the daily mission of a compact car, and this corresponds to an energy pack of 20 kWh, the mass of the required battery is 670 kg if a lead–acid battery is used, or 330 kg with a Ni–MH battery and to 170 kg with a Li–ion battery. This can be compared with about 10 kg of fuel, computed assuming its use with an efficiency of just 15 % (and assuming a 100 % efficiency for the electric motor).

The charge of any battery is critical, since the efficiency and the life of a battery depends on how accurately the energy is introduced into the system. Some batteries

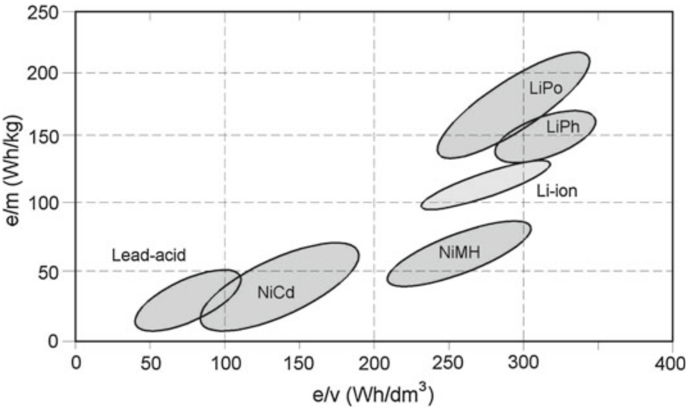

Fig. 12.5 Mass and volume energy density for the main types of secondary batteries

are less critical from this viewpoint, like lead-acid and NiCd cells, although the latter display what is usually referred to as a memory effect, consisting in the tendency to lose some of its capacity when recharged repeatedly after being only partially discharged.

Advanced batteries are more critical, and may even become dangerous if not properly charged, with the risk of fire and explosions. This is solved by using accurately controlled, microprocessor-based, chargers. Battery packs are increasingly provided with on-board electronics that monitor continuously the charge conditions and keeps the current flowing through the various cells under control.

Generally speaking, batteries cannot be used at the same time at high power density and at high energy density: As already stated, when required to supply high power (discharge with high current) the efficiency, and consequently the capacity, decreases. They show also a reduction of their useful life when used in these conditions. Lead-acid batteries are particularly sensitive to this, while some kinds of NiCd and other more advanced batteries can operate with high currents, both during charging (quick charge) and during discharge (high power output).

An ideal battery should be characterized by

- High energy density,
- Almost constant voltage during discharge (a flat discharge characteristics),
- Low internal resistance,
- High discharge current,
- Possibility of operating at both high and low temperatures,
- Long operating life and high number of charge-discharge cycles,
- High efficiency in recharge,
- Low cost.

In several of these points, no actual battery has particularly good performance.

The voltage of a secondary battery decreases during discharge and the plot of the voltage as a function of time is referred to as the discharge characteristics of the cell. Initially there is a sharp drop from the maximum voltage, typical of the fully charged state, to a lower value that is maintained, with a slight decrease, for most of the discharge time. When the discharged conditions are approached there is a sharp drop again. This third phase of the discharge curve must not be used: discharges that are too deep are detrimental to the possibility of fully recharging the battery and can, in the long run, deteriorate it. The discharge curve is much influenced by how fast the discharge is: if the current is large the voltage decrease in the intermediate phase may be larger, depending on the battery type.

At present lead-acid batteries are largely used in the automotive industry, mostly as starting batteries: according to a 2003 report,[2] the batteries of vehicles on the road contained an estimated 2,600,000 t of lead, for a yearly use of over 1,000,000 t. This is made possible only by recycling the old lead from used batteries: in the United States 97 % of all battery lead was recycled between 1997 and 2001. [3] A first difficulty regarding the diffusion of BEV, if done by using conventional lead-acid batteries, is the huge quantities of lead that are required. In 2010 a total of 4.14 MT of lead were mined, and the total production of lead, including recycling, was 9.602 MT, out of which 71 % was used for batteries for various applications. This factor alone would rule out the possibility of converting to battery-electric vehicles a substantial percentage of the vehicles at present on the road: the huge increase of lead to be mined would push the price of this metal beyond what is acceptable for the automotive use.

The situation is not much better with lithium batteries. The annual world production of lithium and the estimated reserves are respectively 18,000 t and 9.9 MT (2009 data[4]): to equip 50 % of the 72 million cars produced in 2007 with a lithium battery containing just 1 kg of lithium each, a total of 36,000 t, twice the annual world production, is needed.

12.3 Hybrid Vehicles

All vehicles considered up to this point work on a single source of energy stored on board, be it the chemical energy contained in a fuel or the electric energy stored in an electrochemical battery. A vehicle that has on board energy stored in two or more forms is said to be a *hybrid* vehicle. A hybrid vehicle must not be confused with a *bimodal* vehicle, that may work both on energy stored on board and energy supplied from the outside during motion, like a trolleybus having a number of electric batteries to obtain a certain off-line range.

A solution to the limited range of electric vehicles consists in associating a second source of power, like a more or less conventional internal combustion engine, to the electric power system. The combined thermal engine-electric batteries hybrid drive

[2] *Getting the Lead Out*, Environmental Defense and the Ecology Center of Ann Arbor, Mich.

[3] http://www.batterycouncil.org/LeadAcidBatteries/BatteryRecycling/tabid/71/Default.aspx

[4] U.S. Geological Survey, 2009, commodity summaries 2009: U.S. Geological Survey.

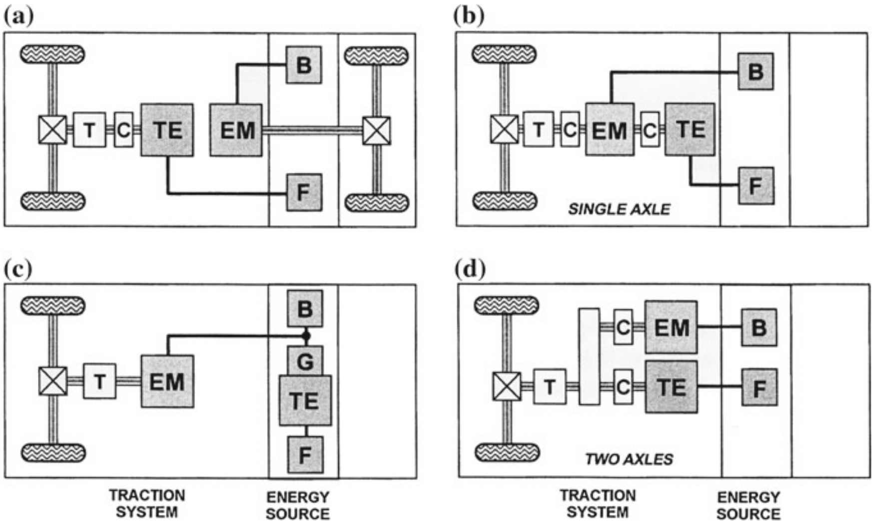

Fig. 12.6 Schemes for hybrid propulsion systems. **a** dual mode propulsion system; **b** series propulsion system; **c** parallel single-axis propulsion system; **d** parallel double-axis propulsion system. *TE* thermal engine, *EM* electric motor, *G* generator, *B* batteries, *F* fuel, *T* transmission, *C* clutch

system lends itself to different interesting applications. However, it is not the only type of hybrid system studied: prototypes of vehicles in which one of the storage system works on elastic energy (hydraulic or pneumatic accumulator), kinetic energy (flywheel) or energy of an electric field (supercapacitors) were studied and even built at a prototype level, and a solution with an internal combustion engine, batteries and flywheel seemed to be particularly interesting. These more complex concepts seem to be interesting for large vehicles, in particular city buses, while only internal combustion engine-battery hybrid systems was seriously considered for cars.

Hybrid drive systems can be used to:

- Drive in highly polluted urban areas in zero emission conditions as an electric vehicle with much less stringent limitations of range,
- improve the energy efficiency of the internal combustion engine since its efficiency decreases together with the power demand; this effect may be obtained by using the internal combustion engine at a higher power than needed to recharge the batteries with the power in excess, and
- recover the kinetic energy during vehicle deceleration for recharging the batteries, while in conventional vehicles brakes would dissipate totally the kinetic energy.

There are essentially three possible hybrid system configurations: *dual-mode*, *series* and *parallel*, as shown in Fig. 12.6. In the dual-mode configuration (Fig. 12.6a), the two drive systems are entirely separate like when using a conventional internal combustion engine to drive the front axle and an electric motor to drive the rear axle. The resulting functions are comparable to those of the parallel hybrid configuration illustrated below.

In the series configuration (Fig. 12.6c), the electric motor drives the wheels and propels the vehicle. The energy is mostly stored in the fuel and transformed into electric energy by the generator driven by the internal combustion engine to be partially stored in a battery and partially directly used to drive the wheels. Series hybrids are designed essentially to minimize emissions, because the internal combustion engine can run in stationary, low emissions, conditions. Moreover, the full potential of the catalytic converter can be used to further minimize emissions.

Parallel hybrids (Fig. 12.6b and d) allow integration of the mechanical energy coming from the fuel through the internal combustion engine and that coming from the batteries through the electric motor. Both can transmit their torque to the wheels, at the same time, working in a strictly integrated way, so that the fuel energy does not undergo a double mechanical/electrical conversion.

With parallel hybrids it is possible to select the size of the electric motor according to the urban missions for which the vehicle is intended (small size), to convert fuel energy into mechanical energy directly and to use the fuel energy if electric power is suddenly unavailable. The electric motor may also be used either to back up the internal combustion engine, by integrating traction power demands, or as a generator for energy recovery during vehicle deceleration.

The parallel hybrid system can be implemented following different configurations. One particularly compact arrangement is the single-axis design (Fig. 12.6b) in which the electric motor is placed between engine and transmission with interposed clutches allowing various operating modes. The two-axle design (Fig. 12.6d) becomes a possibility if the mass of the electric motor can be reduced.

Optimum configuration (series or parallel), size of components and hybrid vehicle management logic depend on the class of vehicle and the missions for which it is intended. Ultimately, a series hybrid configuration is best suited for vehicles intended mainly for urban use, where zero emissions could become mandatory, whereas a parallel hybrid configuration will be expedient for out-of-town use, requiring comparable or better performance than that of thermal engine vehicles.

A particular way of applying hybrid propulsion systems are the so-called *plug-in* hybrids. With these systems the electric energy stored in the battery comes not only from the thermal engine or from the recovered kinetic energy, but also from an external source of energy, like the electric mains; in this case the vehicle is intended to be used as a pure electric vehicle for most of the time, mainly in urban environment, while the thermal engine has the role of a range extender to allow the use of the vehicle when the batteries are discharged or in long journeys.

Before dealing with contemporary hybrid vehicles, a few words must be said about what is usually considered as the oldest hybrid vehicle, the Lohner-Porsche Elektromobil (Fig. 12.7). It was built by Ferdinand Porsche as a BEV and shown at the Paris Exibition in 1900. It had a 61 km range and was peculiar, even in a time when BEVs were common, because of its electric motors located directly in the front wheels. In 1901 it was modified by adding a gasoline internal combustion engine driving a generator to recharge the batteries, becoming a series hybrid vehicle.

The Toyota Prius was the first hybrid car in the world to be mass-produced; it is a parallel single-axis hybrid in which the internal combustion engine and an

Fig. 12.7 The Lohner-Porsche Elektromobil was built in 1900 as a BEV, but was then converted into a hybrid vehicle

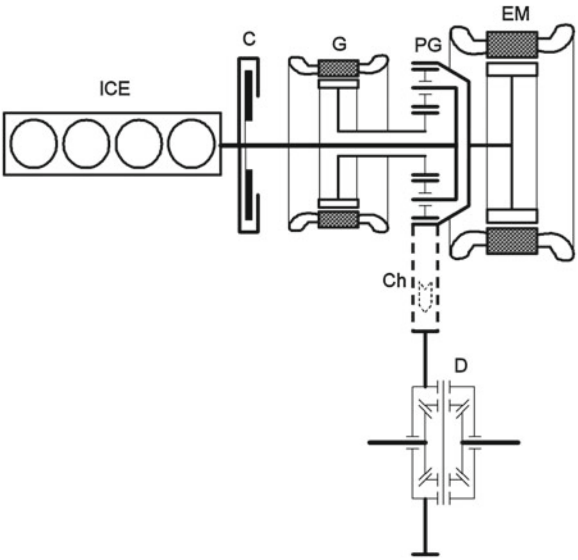

Fig. 12.8 Layout of the hybrid power system of the Toyota Prius; *ICE* thermal engine, *C* automatic clutch, *G* generator, *EM* driving electric motor, *PG* planetary gear, *Ch* chain driving the final gear at the differential D (from Genta and Morello 2009)

electric motor, arranged on the same axle, drive the wheels either separately or at the same time. As shown in the sketch of Fig. 12.8, the system includes a planetary gear for splitting the engine torque between the electric generator and the driveline. The generator, in turn, may either charge the battery or directly power the electric traction motor through the inverter. At start-up and at very slow speed, the electric motor works alone. The heat engine cuts in automatically at medium speed. The planetary

torque splitter (central differential) replaces the gearbox because the electric traction motor seamlessly regulates speed.[5]

This system works both as a parallel and a series hybrid. The angular velocity of the thermal engine adapts to that of the vehicle by changing the speed of the generator, something that can occur only by subtracting a torque, through the generator. By doing this, some power from the thermal engine charges the battery, as in the series layout. At low speed, a part of the power needed for motion is supplied by the electric motor, which takes it from the battery. Finally, at a very low speed only the electric motor operates, as in parallel layouts. This also occurs when the speed of the thermal engine can adapt itself to that of the vehicle, without the generator subtracting any power. When the vehicle slows down, the available kinetic energy is recovered.

This method allows the working range of the thermal engine to be restricted to that where minimum fuel consumption is obtained, for a given power requirement. It is also possible to stop the engine when the vehicle stops and to restart it easily at a speed greater than those at which conventional starter motors operate, owing to the generator that is now used as a motor. The batteries are never recharged from outside the vehicle.

The internal combustion engine operates with gasoline, according to an Atkinson cycle, to reduce pumping losses at partial load, by reducing air intake by a later closing of the intake valve instead of using a throttle valve.

The main specifications given by the manufacturer are:

- Internal combustion engine displacement and maximum power: 1,798 cc and 73 kW at 5,200 rpm;
- Total engine and electric motor power output: 99 kW at 5,200 rpm;
- Permanent magnets electric motor;
- Ni-MH, 200 V batteries;
- Empty vehicle mass; 1,395 kg, and
- Fuel consumption (NEDC): 4 l/100 km.

The Peugeot 3,008 Hybrid 4, shown in Fig. 12.9, is the first hybrid car available with a diesel engine; it is a two-axis parallel hybrid system, in which the internal combustion engine works on the front wheels and the electric motor on the rear axle. In this way an all-wheels drive vehicle is easily obtained from the conventional vehicle with front-wheels drive.

The functions of this system include a start-stop device, with a cranking motor of suitable size; the same auxiliary motor is used for operating an air conditioning compressor, the oil pump for power steering and a vacuum pump for power brakes. The internal combustion engine drives the front axle through a robotized synchromesh gearbox; the electric driveline can simulate powershifs with a suitable control of the traction force.

[5] M. Duoba et al. *In-situ mapping and Analysis of the Toyota Prius HEV Engine*, SAE Paper 2000-01-3096.

Fig. 12.9 The Peugeot 3,008 Hybrid 4 is the first hybrid car available with a diesel engine; it is a two-axis parallel hybrid system, in which the internal combustion engine works on the front wheels and the electric motor on the rear axle (courtesy of Peugeot)

The fuel consumption reduction in comparison with the conventional diesel powertrain with the same power is in the range of 40 % on the New European Driving Cycle. Different control strategies are available:

- For minimum fuel consumption, the electric motor recharges the battery during braking or when the ICE would operate with poor efficiency.
- For maximum performance, the electric motor adds its power to that of the electric motor and the latter improves the vehicle dynamic control with the rear axle torque.
- For Zero Emissions, only the electric motor works, with a reduced range.
- For maximum traction, the electric motor is controlled simulating a limited slip central differential.

The main specifications stated by the Manufacturer are:

- Internal combustion turbocharged Diesel engine displacement: 1,997 cc;
- Maximum thermal power output: 120 kW at 3,750 rpm;
- Maximum thermal and electric power output: 147 kW at 3,750 rpm;
- Permanent magnets electric motor;
- Ni-MH, 200 V batteries;
- Vehicle mass; 1,660 kg;
- Fuel consumption (NEDC): 3,8 l/100 km.

The Opel Ampera, a particular kind of hybrid car, which could also be considered as an extended-range electric car or a plug-in hybrid, provides a final example. It is designed to travel up to 80 km on battery power alone, with a 16 kWh, Li-ion battery pack. When the battery runs low, a compact gasoline powered generator is activated automatically and supplies energy with the sole purpose of allowing driving beyond

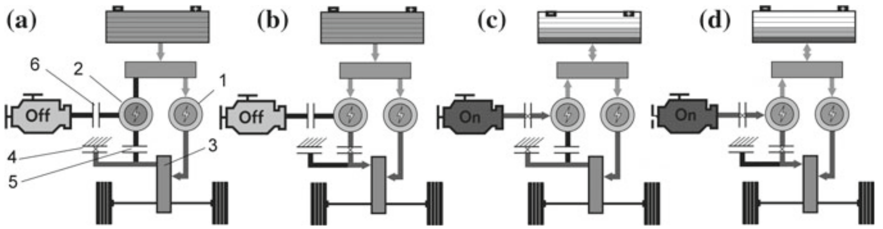

Fig. 12.10 Schemes of the Opel Ampera propulsion system, with two electric motors *1* and *2*, a planetary gear *3* and two electric clutches *4* and *5*. **a** single motor electric mode; **b** dual motor electric mode; **c** single motor extended range mode; **d** dual motor extended range mode (courtesy of Opel)

the range of the battery. It runs at selected speed and load conditions, which have been chosen to supply the requested power with maximum fuel efficiency.

When the engine is running, the system is working as a pure series hybrid one. Obviously, also in these conditions, additional energy recovered during braking is converted into electricity and stored in the battery pack. More precisely, the propulsion system is equipped by two different electric motors 1 and 2, as shown in the scheme in Fig. 12.10a. These units are connected via a planetary gear 3 and two electric clutches 4 and 5, to provide power output for propulsion in four operating modes:

- Single motor electric mode (Fig. 12.10a): The primary motor 1 runs on battery power; its maximum propulsion power is 111 kW; clutch 4 is engaged, while clutch 5 is disengaged; the planetary gear 3 works as a single speed gearbox.
- Dual motor electric mode (Fig. 12.10b): At vehicle speeds higher than 110 km/h, the secondary motor 2 engages over clutch 5; the planetary is free because clutch 4 is disengaged, so that it adds the speed and power of the secondary motor to increase the car speed without further increase of the speed of the primary motor that is running more efficiently. This allows a lower energy consumption to be achieved, without increasing the maximum available power.
- Single motor extended mode (Fig. 12.10c): When the battery reaches its minimum charge, it triggers the combustion engine on. Clutch 4 is again engaged, while clutch 5 is disengaged. The engine drives the secondary motor 2 through the clutch 6, which is now engaged; the motor 2 is used as a generator, to keep the minimum battery charging level. The primary motor can still provide its 111 kW for a short time.
- Dual motor extended mode (Fig. 12.10d): The electric motors are used again in dual configuration with increased efficiency at higher speeds. Additionally, the combustion engine contributes propulsion power via the planetary gear. The power drained from the battery is less than in dual mode electric for the same propulsion power, thus extending the range.

At the end of the mission the battery can be fully recharged in about 6 h by plugging into any standard household 230 V outlet. The battery itself is T-shaped, and is located

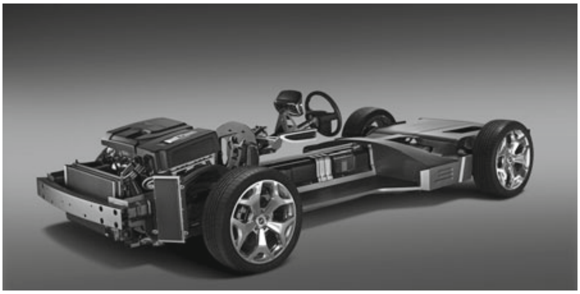

Fig. 12.11 The battery of the Opel Ampera is T-shaped; one branch of the T is along the floor tunnel while the other is across the car, under the rear seat (courtesy of Opel)

centrally in the chassis, as shown in Fig. 12.11; one branch of the T is along the floor tunnel, the other across the car, under the rear seat. This keeps the center of mass low and does not affect the interior space and the baggage compartment significantly.

Main specifications stated by the manufacturer are:

- Displacement of the internal combustion gasoline engine: 1,398 cc.
- Maximum thermal power output: 63 kW at 5,600 rpm.
- Maximum electric power output (primary motor): 111 kW at 3,750 rpm.
- Maximum electric power output (secondary motor): 54 kW at 3,750 rpm.
- Permanent magnets electric motors.
- Vehicle mass: 1,715 kg.
- Fuel consumption (NEDC): 1,2 l/100 km.

According to UN ECE R101 European regulation, fuel consumption in plug-in hybrid cars is calculated with the following formula:

$$C = \frac{D_e C_1 + D_{av} C_2}{D_e + D_{av}},$$

where:

C is the fuel consumption in l/100 km;

C_1 is the fuel consumption in l/100 km, with a fully charged electrical energy storage device;

C_2 is the fuel consumption in l/100 km with the electrical energy storage device in minimum state of charge;

D_{av} is the vehicle's electric range;

D_e is the distance between two battery recharges, assumed to be conventionally 25 km.

Since, in this case, the pure electric range is about 80 km, the electric energy, needed to recharge the battery, should be added to the figure of 1,2 l, needed to drive the car for 100 km, to obtain the total energy cost.

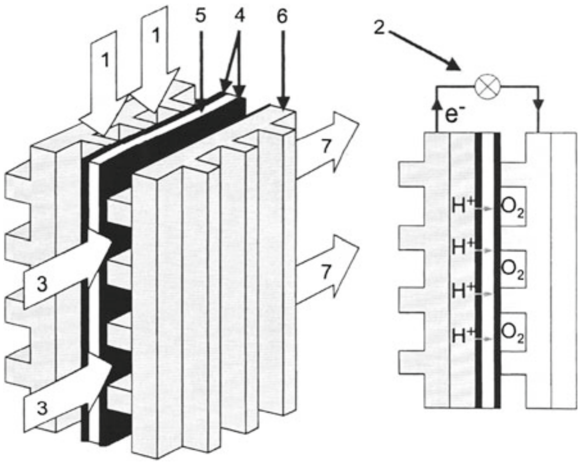

Fig. 12.12 Fuel cells consist of two electrodes *4* separated by an electrolyte *5*. Hydrogen is introduced in the anode area through grooves *1*, while air is introduced through grooves *3*. Nitrogen and water steam are exhausted through the grooves *7*.

12.4 Fuel Cells

The objective of building zero emission drive systems has spurred an increasing interest in developing fuel cells for automotive applications. They are devices that generate pollution-free electric energy by electrochemical reaction of hydrogen with oxygen, producing water as a by-product.

Fuel cells were invented by Sir William Grove in 1839 but were developed in the 1960s for space applications, namely the *Gemini* and the *Apollo* missions and then were widely used on the *Space Shuttle*.

Structurally, fuel cells are similar to batteries (see Fig. 12.12), i.e., they consist of two electrodes (4) separated by an electrolyte (5). However, unlike batteries, they do not use previously accumulated energy. Powered by a fuel (hydrogen) and an oxidant (oxygen), fuel cells generate electrical energy, and can run for as long as the hydrogen fuel supply lasts, but are not rechargeable by electric energy. In this way, the reaction between the fuel and the oxidizer is not a combustion process producing heat that is later converted into mechanical or electric energy, but an electrochemical reaction, producing directly electric energy. For this reason, the efficiency of fuel cells can be higher than that of devices based on thermal engines.

The electrodes of a fuel cell are normally made of graphite with the addition of a catalyst (platinum, palladium, or organic-metallic compounds). Various electrolytes may be used. The most recent developments employ a solid polymeric electrolyte, such as Nafion (brand name of perfluorosulphonic acid), permeable to hydrogen and oxygen ions.

Two conductive plates (6) with built-in grooves are used to organize the flow of the reaction gases. Hydrogen is introduced in the anode area through grooves (1), while air is introduced through grooves (3). In the anode area electrons are released leaving positively charged hydrogen ions. The oxygen, contained in the air and introduced around the cathode, combines with hydrogen ions, acquiring electrons and releasing water steam that is exhausted through grooves (7).

The chemical reaction is:

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O \ .$$

An electric load 2 can close the circuit utilizing the generated energy, that depends on the quantity of hydrogen and oxygen absorbed by the cell. A single fuel cell generates ~ 0.8 V. Cells may be connected in series, forming batteries able of powering an electric motor; in this case, the size of the electric power package is comparable to that of the corresponding conventional internal combustion engine, obviously not including the fuel (hydrogen) tank.

Theoretically, other fuels may be used, but most fuel cells are much sensitive to poisoning by carbon monoxide and impurities, so that operating with fuels other than hydrogen and with oxidizers other than pure oxygen, or in some cases by air (carefully purified) is problematic. This is one of the main reasons that makes the transfer of fuel cell technology from the aerospace field (where pure hydrogen and oxygen are easily available and costs are much less a problem) to the automotive field so difficult.

The catalyst, the electrolyte and the membrane separating the electrodes may be of different types, and consequently different types of fuel calls, each one with its peculiar advantages and drawbacks for the different applications, exist.

- Alkaline fuel cells (AFC) use a liquid, corrosive, electrolyte and must be fuelled by pure hydrogen and oxygen, since impurities in the fuel poison the cell. Their efficiency is about 50 %, or somewhat higher. They are used in space applications since when they were developed for the *Gemini* missions; their building and operating cost is fairly low and they do not require complex ancillary equipment, but are somewhat bulky. Hydrogen-oxygen AFC for space use are a mature technology and need no specific research.
- Proton exchange membrane fuel cells (PEMFC) use a polymer electrolyte and require pure hydrogen as fuel. Contaminants like sulfur compounds and carbon monoxide poison the cell. Owing to their compact design and high energy density they are suited for automotive use, but require complex and costly equipment, like compressors and pumps, that use about 30 % of the energy produced. That notwithstanding, their efficiency is around 30 %. They operate at low temperature, about 80 °C.
- Molten carbonate fuel cells (MCFC) use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic matrix. They are tolerant of the impurities in the fuel and can run on carbon monoxide. Thus they accept different hydrocarbons like natural gas, that can be converted

to hydrogen and carbon oxides or gases made from coal. They operate at high temperatures (650 °C), which reduces their useful life. The efficiency is about 60 %, but can be increased up to 85 % if the waste heat is reused.
- Phosphoric acid fuel cells (PAFC) use liquid phosphoric acid as electrolyte. They are not affected by carbon monoxide impurities in the fuel. Their operating temperature is 150–200 °C. Their efficiency is low (37–42 %), but can be increased if the waste heat is reused. They have a limited service life and use a costly catalyst.
- Solid oxide fuel cells (SOFC) use a solid oxide material as electrolyte. They are not affected by poisoning from carbon monoxide and do not need high-cost, platinum based, catalyst, but are affected by poisoning due to sulfur impurities. The operating temperature is quite high, from 500 to 1,000 °C. Owing to the high temperature, they can use methane, or butane or even liquid fuels that are externally reformed. Their efficiency can reach 60 %, and can be used for cogeneration of electric power and heat. They can operate on light hydrocarbons such as propane and methane without a reformer, or can run on higher hydrocarbons with only partial reforming, but the high temperature and slow start-up time of these fuel cells are problematic for automotive applications.
- Direct methanol fuel cells (DMFC). They are similar to PEMFC, but use directly methanol as a fuel. Their operating temperature is in the range of 50–120 °C, but their efficiency is low, about 20 %. They do not require a reformer, but provide a lower energy density compared to conventional fuel cells, although this could be counterbalanced with the much better volume energy densities of ethanol and methanol over hydrogen. Bio-alcohol fuel is a renewable resource.

If oxygen-hydrogen fuel cells are used, the reaction product is water, that can be stored and again converted into oxygen and hydrogen by an electrolyzer. This combination of fuel cell and electrolyzer is usually referred to as a regenerative fuel cell, and in practice works as a rechargeable battery. No material is consumed (except for some losses) and the system needs only energy.

Much research is at present devoted to fuel cells for vehicular application, both for reducing their cost and for using different types of fuel. The choice of the fuel is quite limited: an interesting alternative to hydrogen is methane, that is much easier to store. If the lower energy density is not a problem, methanol or formic acid can be used as liquid fuel. Recent developments have been aimed at experimenting with direct methanol fuel cells where alcohol instead of pure hydrogen is injected into the cell. Alcohol cells may solve the currently almost insurmountable problems arising from large-scale use of hydrogen, at a cost of a low efficiency. The oxidizer is usually at any rate oxygen.

Current objectives of fuel cell development programs for automotive applications are reducing weight and volume while providing equal levels of available energy and cutting costs.

Systems for storing the fuel (hydrogen) on board and in the supply network—or for producing the fuel on board employing hydrocarbons—must be developed. On-vehicle fuel storage is possibly the biggest problem when designing fuel cell-powered vehicles. Several solutions are being considered, like storing hydrogen gas

in high pressure cylinders (∼300 bar) or in medium-pressure, very low temperature cryogenic tanks. Alternatively, organic fuels (natural gas, methanol, gasoline, diesel) could be suitably treated using on-vehicle systems, to extract the hydrogen needed to fuel the cell pack. The latter approach has the difficulty of meeting the sudden, instant demand for power during acceleration. A solution may involve the use of auxiliary batteries to obtain the instant response needed, although this increases the weight and size of the package. Since the problem of storing hydrogen is a key point in the hypothetical future *hydrogen society*, this point will be dealt with in detail in Part III.

The average tank-to-wheel efficiency of a fuel cell vehicle on a driving cycle like the NEDC is about 36 %, a value to be compared with 22 % of a diesel vehicle, with a maximum of the order of 45 % at low loads. However, if the losses due to hydrogen production, transportation, and storage are taken into account the 36 % efficiency reduces to a power-plant-to-wheel efficiency of 22 % if the hydrogen is stored as high-pressure gas, and 17 % if it is stored as liquid hydrogen. At any rate, fuel cells are efficient relative to combustion engines, but are not as efficient as batteries.

All major manufacturers have produced demonstration prototypes with fuel cell powered drives. System architectures are very different and reflect the different points of view of the various manufacturers and their research establishments. Essentially, architectures fall within two large categories, namely electric-powered vehicles and electric-heat engine powered hybrid vehicles. Within each category, some manufacturers have opted for a pure hydrogen fuel cell system (fuelled with hydrogen in gas or liquid form) while others are developing organic liquid fuel systems (methanol, gasoline, etc.) using reformers to extract hydrogen from the fuel. In this case, batteries are used to cope with power peaks during accelerations.

The variety of solutions is proof of the current uncertainty surrounding developments in product technology and the feasibility of producing new fuels on an industrial scale and distributing them through extensive networks. Fuel cell powered vehicles will become a reality only if international agreements will cause basic technology to converge toward the development of standardized components and a common distribution network for the new fuel (pure hydrogen or other). For obvious reasons, such developments must be seen as long-term projects (∼30 years ahead or more).

12.5 Gaseous Fuels

Gaseous fuels, such as Liquefied Petroleum Gas (LPG) or Compressed Natural Gas (CNG), have always been considered as possible alternatives to gasoline or diesel fuel in motor vehicle engines. Their use only necessitates non-structural changes to the standard gasoline engine and the installation of a special fuel tank. In ordinary vehicles, the tank is nearly always placed in the trunk.

The resulting loss of luggage space in addition to the limited scope of the fuel distribution network, restricted large-scale use to certain historical periods or situations

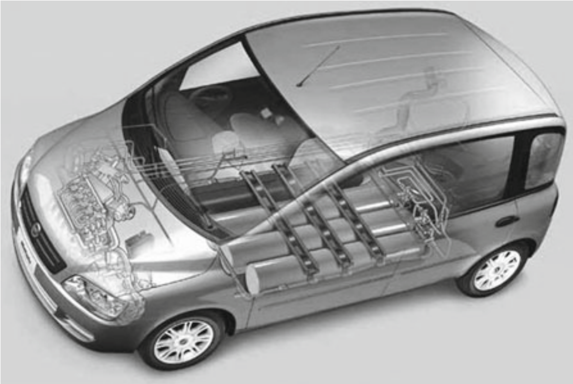

Fig. 12.13 Natural gas vehicle developed by FIAT; the MPV architecture with high floor surface allows an easy installation of gas bottles without negative impact on interior space (courtesy of FIAT)

of fuel shortage. This was the case in Italy in response to pre-war sanctions and immediately after World War II. Today, high taxation on conventional fuels makes the use of natural gas and LPG economically appealing at least on particular vehicles than can easily accept the added fuel tank. This explains why there are about 1,200,000 LPG vehicles and (unknown elsewhere in Europe) some 700,000 natural gas powered vehicles on Italian roads (year 2005).

The need for technological solutions able of lessening the impact of vehicle traffic on the environment has recently given impetus to the development of vehicles operating on gaseous fuels. They do not contain aromatic hydrocarbons or olefins and therefore the unburned hydrocarbon emissions deriving from their use are less reactive and less toxic than the emissions of unburned hydrocarbons from gasoline and diesel engines.

The carbon content of butane and propane molecules (the basic components of LPG) or natural gas is lower than that of hydrocarbon molecules in gasoline and diesel fuel. Consequently, for the same fuel consumption by weight, CO_2 emissions are also lower. With these considerations in mind, the ideal gaseous fuel would be hydrogen because, if burned in an engine of a conventional power plant, its emissions would be very low, namely no CO_2, CO or particulate, low NO_x (which is inevitable on account of the nitrogen content of air), and minimum hydrocarbon (due only to the burnt oil).

An example of natural gas vehicle (actually, a gas-gasoline bi-fuel vehicle) developed by FIAT is shown in Fig. 12.13; the MPV architecture with high floor allows an easy installation of gas bottles without negative impact on interior space . The bi-fuel system is needed since the fuel supply network of natural gas for automotive purposes is still scanty and non-existent in some areas.

Compressed natural gas is stored in cylinders at 200 bar and therefore in gaseous form; this normally limits the vehicle range because of the limited space available,

but this kind of vehicle can accommodate large volume cylinders that allow a range of about 500 km, comparable to that of conventional vehicles.

A possible evolution is the storage of natural gas in liquid form employing very low temperature cryogenic tanks. This solution has already been implemented on trucks and is being tested in the USA. Thus, natural gas systems may offer an opportunity to test and refine a technology, which will be required if hydrogen is going to be the fuel of the future. All LPG vehicles marketed today feature also a dual fuel gas-gasoline engine. Again, this is done to offset the limitations of the fuel supply network.

LPG is easily stored as a liquid in tanks at a pressure of 7 bar. The presence of two tanks, one for LPG and one for gasoline, causes problems similar but with lower impact on space than those of natural gas vehicles. However, on account of the higher density of the fuel, the range with a full tank of LPG is 400–450 km.

Natural gas is perhaps the gaseous fuel offering the largest advantages, since it is:

- An excellent fuel with high octane rating. In natural gas-only engines, this property allows partial recovery of the loss of volumetric efficiency due to the low density of natural gas;
- available in nature in large volumes in various areas of the planet, not necessarily in oil fields;
- readily available in Europe thanks to a capillary distribution network;
- obtainable by decomposing organic waste and, finally,
- the fuel closest to hydrogen because its molecules have a highest hydrogen/carbon atomic ratio.

Therefore, it is a true alternative fuel, capable of relieving the current dependency on petroleum as a source of energy for motor vehicles. Various programs are currently underway in many European centers in an effort to refine natural gas technology for application to a wide range of vehicles, including buses, trucks, door-to-door delivery vans, taxis, private cars and utility vehicles.